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High-mass X-ray binary SXP18.3 undergoes the longest type II outburst ever seen in the Small Magellanic Cloud

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ABSTRACT

On 2006 August 30, SXP18.3 a high-mass X-ray binary (HMXB) in the Small Magellanic Cloud (SMC) with an 18.3 s pulse period was observed by *Rossi X-ray Timing Explorer* (*RXTE*). The source was seen continuously for the following 36 weeks. This is the longest type II outburst ever seen from a HMXB in the SMC. During the outburst, SXP18.3 was located from serendipitous *XMM–Newton* observations. The identification of the optical counterpart has allowed SXP18.3 to be classified as a Be/X-ray binary. This paper will report on the analysis of the optical and weekly *RXTE* X-ray data that span the last 10 yr. The extreme length of this outburst has for the first time enabled us to perform an extensive study of the pulse timing of a SMC Be/X-ray binary. We present a possible full orbital solution from the pulse timing data. An orbital period of 17.79 d is proposed from the analysis of the Optical Gravitational Lensing Experiment (OGLE) III light curve placing SXP18.3 on the boundary of known sources in the Corbet diagram.

Key words: stars: emission-line, Be – Magellanic Clouds – X-rays: binaries.

1 INTRODUCTION

Over the past 20 yr, the number of known high-mass X-ray binaries (HMXBs) located in the Small Magellanic Cloud (SMC) has been steadily increasing. There are now 58 known HMXB pulsar systems in the SMC (Coe et al. 2005). Systems where the counterpart is a Be star form the largest subclass of HMXBs. Within the SMC, all but one system (SMC X−1) are found to have Be star counterparts. McBride et al. (2008) find that the spectral distribution of these counterparts is consistent with the distribution found in the Galaxy. From studies of Be/X-ray binaries in the Galaxy, it has been found that the compact object, presumably a neutron star is generally in a wide and eccentric orbit. X-ray outbursts are normally associated with the passage of the neutron star close to the circumstellar disc (Okazaki & Negueruela 2001). Detailed reviews of the X-ray and optical properties of such systems may be found in Coe et al. (2005) and Haberl & Pietsch (2004), a review of the more general properties can be found in Coe et al. (2000).

1.1 SXP18.3 = XTE J0055 − 727 = XMMU J004911.4−724939

SXP18.3 was discovered in 2003 during routine *Rossi X-ray Timing Explorer* (*RXTE*) proportional counter array (PCA) observations of the SMC (Corbet at al. 2003). They report detecting pulsations with a period of 18.37 ± 0.1 s. *RXTE* slew observations were able to narrow the position down to an ellipse with RA = 13°.84 ± 0.1 and Dec. = 72°.70 ± 0.06, however, no firm identification of an optical counterpart was possible. Five detections of SXP18.3 were made in 2004. Corbet at al. (2004) noted that these detections appeared to be occurring on a 34.8 d period and proposed this as the orbital solution. From the full analysis of the X-ray light curve prior to the large outburst, Galache et al. (2008) refined this period to 17.37 ± 0.01 d (approximately half of the value proposed by Corbet at al. 2004). On 2007 March 12–13, SXP18.3 was identified serendipitously through a 39 ks *XMM–Newton* observation of the emission nebula N19 in the SMC (Eger & Haberl 2008; Haberl, Eger & Pietsch 2008). They report the presence of a bright X-ray transient source showing pulsations at 18.3814 ± 0.0001 s, at RA = 00:49:11.4, Dec. = −72:49:39 with a positional uncertainty of 1.18 arcsec. The detection of these pulsations confirms the identification as being SXP18.3 and enabled the optical counterpart to be identified. In this

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Table 1. Optical counterpart matches. 'Distance' refers to the offset of the object from the *XMM–Newton* position.

Catalogue	Reference ID	RA	Dec.	Distance (arcsec)	Date (MJD)	U	B	V	I
MCPS[1]	1933826	00:49:11.53	−72:49:37.2	0.11	–	15.22 ± 0.03	16.01 ± 0.02	15.96 ± 0.03	15.89 ± 0.04
MACHO[2]	208.15911.13	00:49:11.42	−72:49:36.1	1.31	48855-51527	–	–	16.0–15.2	16.0–15.4
Catalogue	Reference ID	RA	Dec.	Distance (arcsec)	Date (MJD)	I	J	H	K_s
OGLE II[3]	smc_ sc5 65500	00:49:11.45	−72:49:37.1	0.45	50466-51871	16.0-15.2	–	–	–
OGLE III[4]	SMC101.8 19552	00:49:11.45	−72:49:37.1	0.45	52086-54487	15.9-14.8	–	–	–
2MASS[5]	00491147-7249375	00:49:11.47	−72:49:37.6	0.43	51034	–	15.9 ± 0.1	>15.119	15.6 ± 0.2
SIRIUS[6]	00491143–7249375	00:49:11.43	−72:49:37.5	0.52	52517	–	16.05 ± 0.02	16.03 ± 0.03	16.13 ± 0.05

[1]Zaritsky et al. (2002), [2]Alcock et al. (1999), [3]Udalski, Kubiak & Szymański (2005), [4] private communication, [5]Skrutskie et al. (2006) and [6]Kato et al. (2007). SIRIUS, Simultaneous 3-COLOR Infrared Images.

paper, we present the analysis of both the long 10 yr optical and X-ray light curves, as well as constraints on the orbital parameters derived from detailed timing analysis of the detected pulse period.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Optical observations

The optical counterpart is clearly identified by the *XMM–Newton* position by Eger & Haberl (2008) as a $V = 16$ mag star (Zaritsky et al. 2002). This counterpart is present in a number of optical catalogues of the SMC. These data are summarized in Table 1, where we also quote the positional offset from the *XMM–Newton* position. The optical magnitudes both in the visual range and infrared are typical of the many Be star counterparts that are associated with the other Be/X-ray binaries in the SMC (Coe et al. 2005; Schurch et al. 2007).

To compare the Magellanic Clouds Photometric Survey (MCPS) photometry (Table 1) with standard stellar models (Kurucz 1979), the data were first corrected for the standard reddening to the SMC of $E(B-V) = 0.09$ (Schwering & Israel 1997). The dereddened MCPS colour $(B-V) = -0.04$ is typical of the Be star counterparts found in the SMC (Shtykovskiy & Gilfanov 2005; McBride et al. 2008). This colour suggests an optical counterpart in the range B0–B2. Fig. 1 shows the dereddened MCPS U, B and V fluxes plotted over possible Kurucz stellar atmosphere models. The U and B fluxes suggest that the counterpart is in fact B2V, whilst the V flux indicates that there is a red excess typical of a circumstellar disc. This classification will need verification from detailed spectrographic measurements. However, in light of this fit we support the proposal by Eger & Haberl (2008) that SXP18.3 is a Be/X-ray binary.

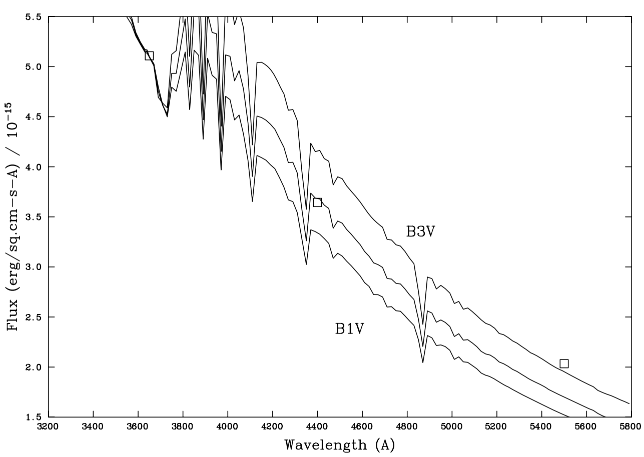

Figure 1. Comparison of U, B and V MCPS fluxes, dereddened by $E(B-V) = 0.09$, with Kurucz stellar atmosphere models.

2.1.1 *Optical light curves*

From the combined OGLE II and III light curves, we scaled the instrumental massive compact halo object (MACHO) magnitudes so that the continuum of both the OGLE II and MACHO data aligns. Shifts of +24.81 and +24.55 mag were applied to the blue and red MACHO data, respectively. The bottom panel of Fig. 2 shows the combined light curve from 1992 August to 2008 April (only the overlapping MACHO data are shown). The full MACHO red and blue light curves are shown in Fig. 3. As is clearly seen there have been a number of large distinct optical outbursts. The first two lasted for 500–600 d each, and later one giant outburst started around MJD 52800 that lasted for around 1500 d. After each outburst, the optical flux has always returned to an approximately steady base value of ∼16.0–15.9 mag. The simultaneous red and blue MACHO data allow the colour changes throughout the first two optical outbursts to be examined. It is clear that as each of the

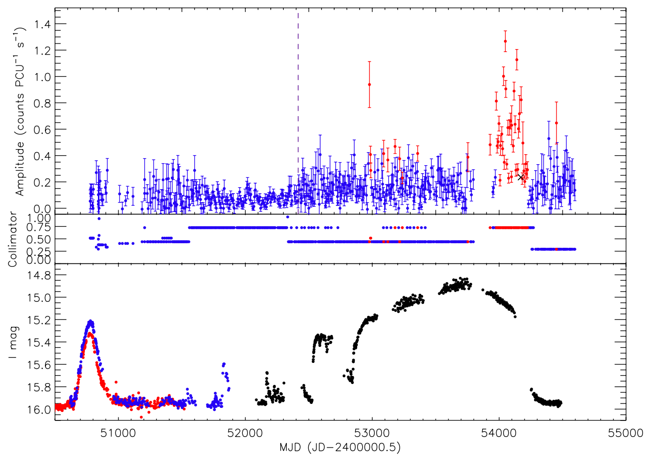

Figure 2. SXP18.3 X-ray and optical light curves. Panels are PCA pulsed flux light curve in the energy range 3–10 keV (top panel), PCA collimator response (middle panel), combined MACHO (red), OGLE II (blue) and III (black) light curves (bottom panel). The black cross represents the *XMM–Newton* detection (MJD 54171) and the dashed line indicates a non-detection by *Chandra* ACIS-I, observation 2944 (MJD 52416). The red points in the *RXTE* light curve and collimator response represent detections of the source above a 99 per cent local significance level.

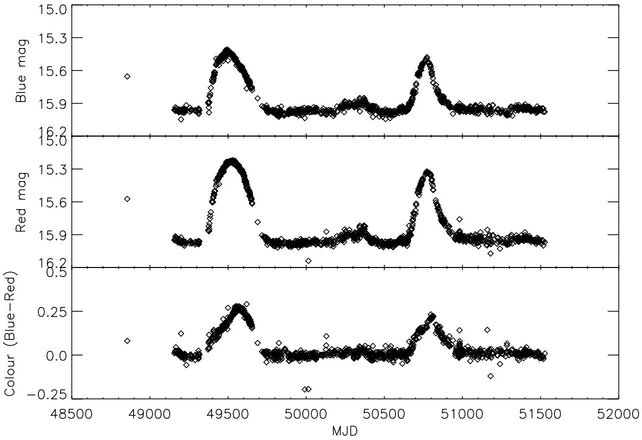

Figure 3. MACHO red and blue light curves and colour variations.

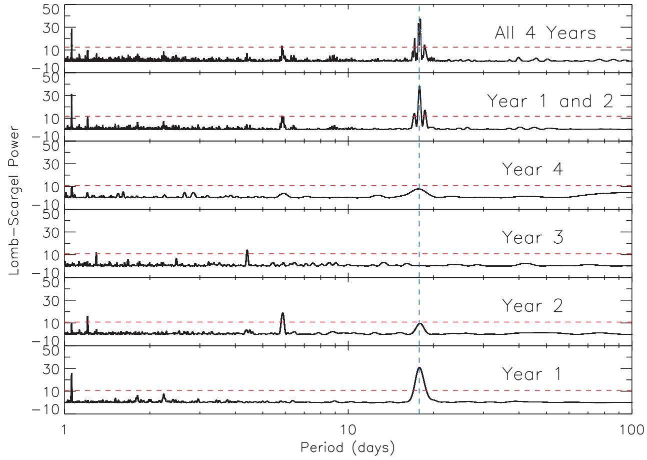

Figure 4. Power spectra of the four year detrended OGLE III light curve. The dotted horizontal red lines indicate the 99 per cent significance level and the dotted vertical blue line indicates the 17.79 d period.

outbursts proceeded the source slowly reddens. After the peak of the outburst is reached, the colour returns to its baseline configuration. It is worth noting that the colour change is asymmetrical. Similar behaviour is also observed in SXP6.85 McGowan et al. (2008). As was suggested in McGowan et al. (2008), the colour variation would likely indicate changes in the structure of the circumstellar discs. Either the formation of the disc is increasing the optical brightness by the addition of red light or the large disc is now masking out part of the surface of the bluer Be star, behaviour that is dependant on the inclination angle of the system.

2.1.2 Orbital period

The large optical outbursts seen in the light curve are too bright and occur on vastly longer time-scales than would be expected for this source if they were due to the orbital period (∼20–100 d from the Corbet diagram). We attribute them to changes in the size of the circumstellar disc. However, a search for possible binary modulations was carried out on the detrended data. Removing the large variations without introducing artificial variations and features proved to be extremely difficult. Periods when the light curve is changing very fast are impossible to detrend meaningfully. We thus restricted the search to the last four years of OGLE III data (MJD 53164.9 to 54487.6) where we have been able to detrend the data by subtracting linear fits. A single linear fit was used for the first three years. The fourth year of data was first split in half and then separate linear fits were used for each half. The resultant light curve was searched as both a whole and as individual years for periodicities in the range 1–100 d using Lomb–Scargle (LS) periodograms.

The results of the temporal analysis are shown in Fig. 4. A clear peak well above the 99 per cent significance level occurs at 17.79 ± 0.01 d in the first two years of our detrended OGLE III data, in agreement with Udalski & Coe (2008). This periodicity then disappears completely during the third year only to reappear at a much lower significance in the fourth year at a slightly different period. The lobes in the combined year 1 and 2 data are due to the 17.79 d period beating with the one year sampling. The very short period peaks (around 1 d) are due to the one day sampling of the data. We also note the high peaks at 5.87 d in the year 2 data and the peak at 4.40 d in the year 3 data. These peaks are not the third and fourth harmonics (respectively) of the higher period peak at 17.79 d. As a consequence of its strength, the 5.87 d peak appears in the combined data; however, the structure has become very double peaked. No periodic variations were found in the MACHO or OGLE II data. This optical period, which we interpret as the orbital period, places this HMXB well within the limits of the proposed Be/X-ray binaries on the Corbet diagram (Coe et al. 2008; Corbet et al. 1999). The ephemeris of the outbursts is MJD $(53178.3 \pm 0.8) + n(17.79 \pm 0.01)$.

2.2 *RXTE* observations

Reviews of our ongoing *RXTE* X-ray monitoring programme of the SMC may be found in Galache et al. (2008) and Laycock et al. (2005). During 2006, a trial observation at Position 5 (12°.5, −73°.1) revealed two pulsars to be in outburst, SXP18.3 and SXP15.3. From 2006 August 3 (MJD 53950) till 2007 June 19, this position was monitored weekly. After three weeks of monitoring on 2006 August 30 (MJD 53977), SXP18.3 switched back on. The source remained in outburst and was continually detected every week for the next 36 weeks finally disappearing on 2007 May 3 (MJD 54223). This was the longest uninterrupted outburst ever seen in the SMC. Fig. 2 shows the full 10 yr of *RXTE* monitoring, the collimator response represents the position of the source within the field of view (FoV) of *RXTE* (one being at the centre and zero at the edge). The red points represent where 18.3 s pulsations above a 99 per cent local significance level have been detected in the power spectra of *RXTE* light curves. The blue points represent no detection. For specific details of the data processing, see Galache et al. (2008). As can be seen prior to the massive outburst, the source was only seen in outburst on seven occasions. These outbursts do not correlate to any particularly interesting features on the optical light curve.

We have estimated the range of luminosities for this outburst using Portable, Interactive Multi-Mission Simulator (PIMMS) v3.9f[1] and assumed a distance to the SMC of 60 kpc. We used the spectral fit found from the *XMM–Newton* observations (Eger & Haberl 2008) ($\Gamma = 0.65$, $N_H = 2 \times 10^{22}\,\mathrm{cm}^{-2}$) and assumed that the *XMM–Newton* measured pulse fraction of 21 ± 3 per cent remained constant for the entire observation. The *RXTE* luminosity range throughout the outburst is $L_{0.2-10} = (0.51-3.2) \times 10^{37}\,\mathrm{erg\,s}^{-1}$.

[1] http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html

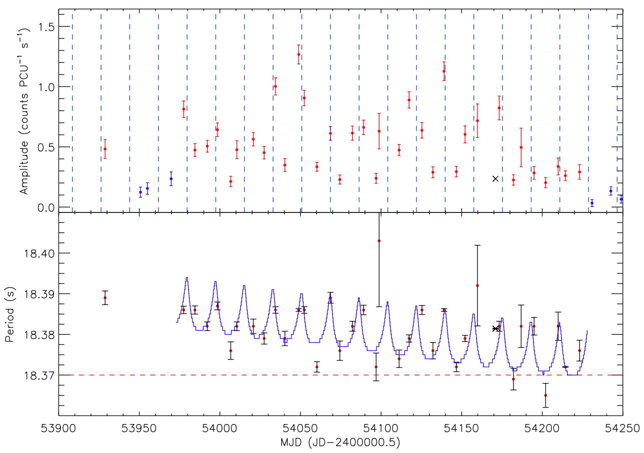

Figure 5. SXP18.3 X-ray outburst. Top panel shows the *RXTE* amplitude (red points are above 99 per cent significance) with the vertical dotted lines showing periastron passage as predicted by the optical light curve. The bottom panels show the detected *RXTE* pulse periods with the orbital solution over plotted. The black crosses are the *XMM–Newton* detected pulse period (orbital phase 0.80) and flux converted to *RXTE* with PIMMS v3.9f.

2.2.1 *Orbital fitting*

Fig. 5 shows in detail the detected luminosities and pulse periods throughout the nine month long X-ray outburst. It is evident from the general trend in the detected pulse period (bottom panel) that SXP18.3 was spinning up during the outburst. This general spin up equates to a luminosity of $L_{3\text{–}10} = 2.67 \times 10^{36}$ erg s $^{-1}$ (Ghosh & Lamb 1979). The shorter variations occurring throughout the outburst suggest that the detected spin period is being orbitally modulated. We detrended the data and performed a LS period search revealing a peak in the power spectrum above the 99 per cent significance level at 17.62 ± 0.1 d. This period would seem to be consistent to that found in the optical data. We have thus tried to fit a full orbital solution to the pulse period values. The orbital fitting is performed by a χ^2 minimization method. We performed two fits, the first allowing all the parameters to vary, and in the second we fixed the orbital period to that found from the optical light curve. Subsequent folds of the *RXTE* light curve using the first fit appeared quite chaotic and unbelievable, hence the model is not presented. In Fig. 5, we show the orbital fit to the data with the orbital parameters shown in Table 2. It is worth noting that the time of periastron passage is consistent with that from the independent analysis of the optical data. The orbital parameters are typical of those seen in other accreting Be/X-ray binaries (Okazaki & Negueruela 2001), most Be systems have $P_{\rm orbital} \sim$ 20–100 d with eccentricities in the range 0.3–0.5 (Bildsten et al. 1997).

Table 2. Orbital parameters.

Parameter	Orbital Solution
$P_{\rm orbital}$ (d)	$17.79_{\rm fixed}$
$a_x \sin i$ (light s)	75 ± 3
ω (°)	15 ± 6
e	0.43 ± 0.03
$\tau_{\rm periastron}$ (MJD)	$53\,997.6 \pm 0.2$
$P_{\rm spin}$ (s)	18.3854 ± 0.0004
$\dot{P}$ (s yr^{-1})	$(-1.79 \pm 0.11) \times 10^{-2}$
χ^2_ν	8.22

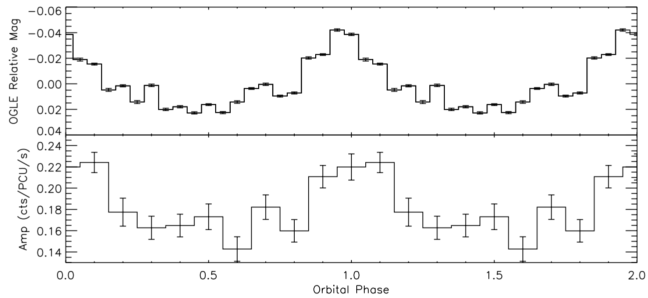

Figure 6. *RXTE* (bottom panel) and OGLE (top panel) folded light curves.

We have folded the first two years of the detrended OGLE III light curve and the *RXTE* amplitude measurements to evaluate the orbital solution. The *RXTE* data are folded in 10 bins and the OGLE III data have been folded in 20 bins using the orbital period and ephemeris from Table 2. Both the X-ray and optical folded light curves (bottom and top panel, respectively, of Fig. 6) have fairly sinusoidal profiles and are well matched with the peaks coinciding. This would suggest that 17.79 d is the orbital period. There is also another probable peak in the optical data at phase 0.7 with some hint of its presence in the X-ray fold.

2.2.2 *RXTE spectra and pulse profiles*

Because *RXTE* has such a large field of view, we constantly cover many SMC sources in our observations. This makes it extremely difficult to resolve one source from another. Due to the unusually large outburst from SXP18.3, there were several observations where our analysis revealed that it was the only known source to be in outburst. We placed further restrictions on which observations were suitable for analysis by only examining those observations when the source was detected above the 99 per cent global significance level (for details see Galache et al. 2008). We examined the spectra of 18 out of the 35 observations in the 3–10 keV range. Although SXP18.3's outburst was very long it was never particularly bright, hence the spectra have a low signal-to -noise ratio. We attempted to fit each spectrum with an absorbed power law and tried both fixing the absorption to that of the SMC and allowing it to vary. We were unable to produce any meaningful fits to the spectra. This is most likely due to the unknown contamination from background active galactic nuclei (AGN), and X-ray binaries emitting at a very low level.

In addition to analysing the spectra, we have also examined the pulse profiles for each of these observations. We used the ephemeris and orbital period from Table 2 to calculate the orbital phase for each observation (shown on each pulse profile), the observations were then arranged to appear in order of their orbital phase, duplicated orbital phases were removed (Fig. 7). In each case, an arbitrary pulse phase shift was applied to align the main peak of the profile with phase zero. The majority of the pulse profiles present a very similar sinusoidal shape with a very steep rise and gradual fall, in good general agreement with those presented in Haberl et al. (2008). The pulse profiles around periastron passage appear to be fairly stable with small changes to the shape of the fall off. There is some emission that is associated with pulse phase 0.5 with a subsequent steep decline to minimum emission occurring at pulse phase 0.7–0.8. This emission is possibly due to either the X-ray beam fanning out and becoming more conical in shape allowing emission from the second pole to be seen, or that the accretion

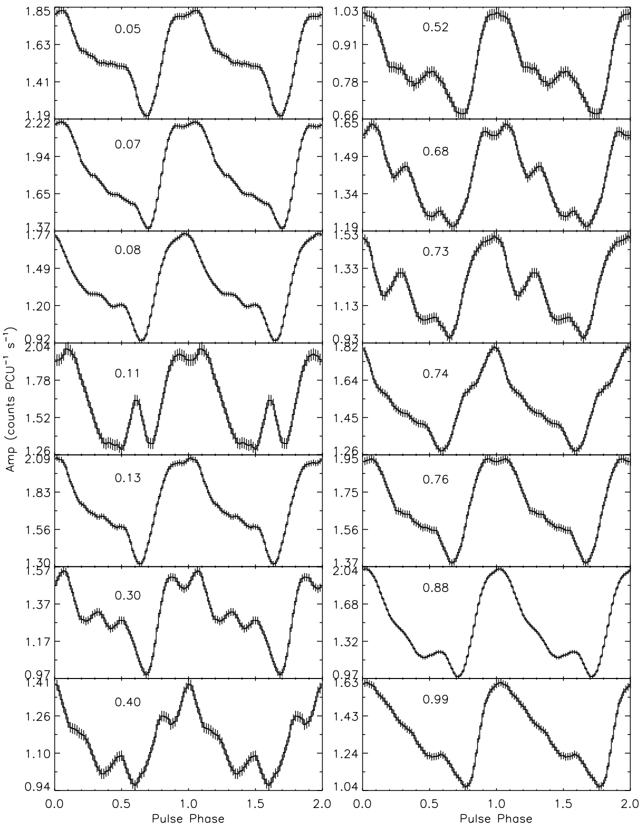

Figure 7. Folded pulse profiles of SXP18.3, an arbitrary pulse phase shift was applied to align the peaks since they cannot be phase locked between observations. Arranged in order of orbital phase (given in the label) starting at the top left.

stream is preferential to one pole and only occasionally splits to both the poles. When the neutron star is around apastron (orbital phase 0.3–0.7), the pulse profiles become rather more complicated with several additional peaks emerging. We have used these pulse profiles to measure the pulsed fraction to be in the range 22 ± 10 per cent. This is consistent with the value found from the *XMM–Newton* observations. There is also a strong correlation between the pulse fraction and observed amplitude, suggesting that although the source would appear to vary throughout the outburst (Fig. 5), it is infact emitting at an almost constant stable rate.

3 DISCUSSION

The optical and X-ray data suggest that SXP18.3 is a HMXB transient. From the analysis of the MCPS data, we have proposed a tentative classification of the counterpart as B2V, supporting the proposal by Eger & Haberl (2008) that SXP18.3 is a Be/X-ray binary. The optical light curve of SXP18.3 shows periods of extreme brightening occurring over very long time-scales. These dramatic outbursts are seen to occur in many other Be/X-ray binary systems (e.g. SXP46.6, SXP6.85 McGowan et al. 2008) and are most likely due to massive size variations in the circumstellar disc surrounding the Be star. In particular, SXP6.85 (McGowan et al. 2008) exhibits similar recurrent optical outbursts of comparable duration and brightness. Complex computer simulations are required to understand the exact nature of these optical outbursts and how they produce the colour variations. The 17.79 d period found in the optical data is interpreted as the orbital period of the neutron star round the Be star. If we assume that the equatorial plane of the Be star is approximately coincident with that of the neutron stars orbit, then as periastron is approached we see some distortion of the circumstellar disc due to the larger gravitational attraction between the two objects (Okazaki & Negueruela 2001). These distortions would temporarily increase both the size and luminosity of the disc. This orbital modulation is seen in many Be/X-ray binary systems (Coe et al. 2008).

It is interesting that the orbital modulation is not always present, only being significantly detected when the *I* magnitude of the Be star is brighter than 15.2 mag. This suggests that the disc has to be sufficiently large and hence close to the neutron stars orbit for any significant perturbations. However, we note that during the massive X-ray outburst there is no modulation in the optical data. This is possibly due to the extreme nature of this outburst. Here, we may have a situation where the disc has possibly grown to such a size that it is encompassing the entire orbit of the neutron star, allowing continuous accretion. Assuming typical values for the mass of the Be and neutron star and the orbital period found, we would expect a semimajor axis of $\sim 85\,R_{\odot}$. From Hα equivalent width measurements, Grundstrom et al. (2007) have estimated the disc radius in the Be/X-ray binary A0535+26 to reach a maximum size of $90\,R_{\odot}$. It is not unreasonable to envisage a disc growing to this size and producing such a massive outburst. If this situation is correct then the perturbation suffered by the disc may increase the local density of material rather than extend the physical size of the disc, resulting in the orbital signature disappearing. One problem with this interpretation is explaining the orbital signature seen in the first two years of detrended OGLE III data. If the optical outburst is attributed to the disc growing in size then during these two years, the disc is larger or denser than when we observed the X-ray outburst. If the model proposed is correct then the neutron star would have been within the disc for this entire period and we should have seen no optical signature and possibly even X-ray outbursts. Unfortunately, for the majority of this period SXP18.3 was outside the central 1° of *RXTE*'s FoV, thus having a much lower detection sensitivity. SXP18.3 may have dropped below this threshold and hence we cannot say for definite that SXP18.3 was truly off. It is interesting to note that prior to the massive X-ray outburst we only detected SXP18.3 on a handful of occasions, all during periods when $I <$ 15.2 mag.

We attempted to fit a full orbital solution to the variations in the observed spin period. Our foremost problem with this fit is that the data sampling is too infrequent to allow us to take into account the variations in the accretion torques. This will manifest its self as deviations away from our orbital solutions. Even though we have data spanning many orbital cycles during the outburst, the fact that we only have two or three data points per orbital cycle is simply insufficient to properly constrain the orbital parameters. However, the close match between the X-ray and optical folded light curves clearly suggests that 17.79 d is the true orbital period.

SXP18.3 lies in the bottom left-hand corner in the low orbital and spin period regime of the Corbet diagram. It is right on the extremity of the distribution of Be/X-ray binaries. If this source was to move slightly further to the left (lower orbital period) then it would start to fall into the Roche lobe overflow group. When we examine the type of outbursts exhibited by SXP18.3, we see that there are a couple of short-lived typical type I outbursts just above our detection threshold, and then the massive 36 week type II outburst. Outbursts of this length are extremely rare for Be/X-ray binaries, since for the duration of this period the neutron star must be accreting constantly. SAX J2103.5+4545 is a Be/X-ray binary where similar X-ray behaviour is seen (Baykal, Stark & Swank 2002). It is a pulsar with a long spin period of ∼359 s but a very short orbital period of 12.7 d (comparable with SXP18.3). This would place it at the top left of the distribution of Be/X-ray binaries in the Corbet diagram. SAX J2103.5+4545 has exhibited several bright X-ray phases lasting hundreds of days, with luminosities $\sim 10^{36}$ erg s^{-1}. It is only during these bright phases when the orbital period has been detected. Blay et al. (2004) suggest that this could be due to the density/size of the circumstellar disc being large enough to temporally fill its Roche lobe during periastron, and hence temporally allow accretion to take place. It could be that the moderately bright outburst seen in SXP18.3 is due to a very similar mechanism which produces the outbursts seen in SAX J2103.5+4545. We could imagine that these short orbital period systems possibly flip between states of Roche lobe overflow and quiescence. Monitoring the state of the Hα line before, during and after an outburst would help shed some light on these systems. Be/X-ray binary systems like these may well be providing an indication of a lower limit for Be/X-ray binaries on the Corbet diagram.

4 CONCLUSIONS

In light of the optical and X-ray data, we feel that SXP18.3 is the newest member of the group of transient Be/X-ray binaries in the SMC. The proposed orbital model requires intensive observations and detailed computer simulations to fully assess the parameters and explain the presence of the second optical peak. We are now beginning to explore the limits of the Corbet diagram where mixtures of behaviours are observed and sources like SXP18.3 are key to this study.

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